The PBL-focused data assimilation in the GMAO GEOS global system

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Challenges in PBL-focused data assimilation

- Accurate simulation for the PBL conditions including PBL height is important to many applications
- PBL is an important interface between the earth and its atmosphere, core to understanding the flux balances across the earth system components
- The Planetary Boundary Layer was listed as an ‘Incubation’-class targeted observable in the 2017 NASEM Earth Science Decadal Survey

Difficulties we are facing with PBL-focused data assimilation

- High degree of spatial and temporal heterogeneity at the surface and in the PBL, diurnal variations
- Complicated interactions between the land/ocean surface and atmospheric planetary boundary layer
- Uncertainties of land surface model and PBL parameterization schemes
- Lack of comprehensive observations
- Observation influence depends on atmospheric conditions --Implications on background error vertical correlation length and ensemble vertical localization length
- Assimilating surface- and cloud-sensitive radiances is still challenging

Limitations in the existing observations & their usages
-- No perfect observing systems for global PBL

- Radiosonde data: T/q/uv, but not adequate vertical & temporal resolution; concentrated over land
- Aircraft data: abundant at takeoff & landing near airports and cruise level
- Near-surface observations: T2m, q2m, w10m are not used
- Satellite AMV: often single level observations, and presence of high clouds prevents retrieval of AMV winds at middle/lower levels
- GPS RO: not used at lower troposphere, coarse along-ray but high-vertical resolution. Testing on using COSMIC-2 GNSS-RO at lower levels is underway
- Microwave radiances: broader weighting function & coarser resolution, but can penetrate clouds, good data coverage
- Infrared radiances: hyperspectral/geostationary, but can't provide info beneath clouds

4D data assimilation can utilize data from multiple observing systems coherently to construct better thermodynamic structure for the global PBL

The hybrid 4DEnVar GEOS data assimilation system

$$J(\mathbf{x}'_c, \mathbf{a}) = \beta_c \frac{1}{2}(\mathbf{x}'_c)^T \mathbf{B}_c^{-1}(\mathbf{x}'_c) + \beta_e \frac{1}{2}\mathbf{a}^T \mathbf{L}^{-1}\mathbf{a} + \frac{1}{2}\sum_{k=1}^{K}(\mathbf{H}_k \mathbf{x}'_{(t)k} - \mathbf{y}'_k)^T \mathbf{R}_k^{-1}(\mathbf{H}_k \mathbf{x}'_{(t)k} - \mathbf{y}')$$

$$\mathbf{z} = \mathbf{B}^{-1}\mathbf{x}'_c \qquad \mathbf{v} = \mathbf{L}^{-1}\mathbf{a}$$

Where the 4D analysis increment is prescribed through linear combinations of the 4D ensemble perturbations plus static contribution.

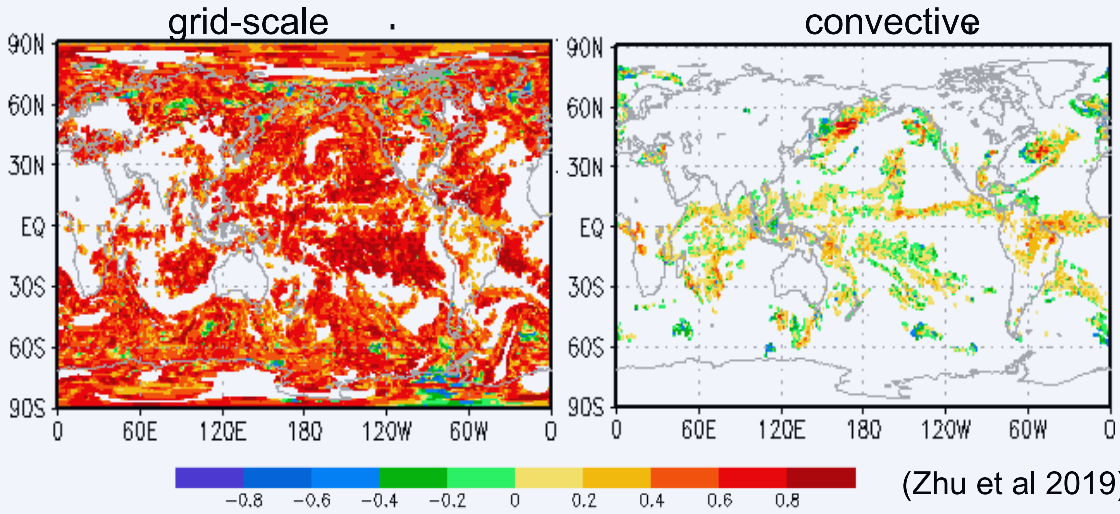
$$\mathbf{x}'_k = \mathbf{C}_k \, [\mathbf{x}'_c + \sum_{m=1}^{M}(\alpha^m \circ (\mathbf{x}_e)_k^m)]$$

- GEOS data assimilation system **provides the capability of combining model physics and a wide range of observations** to generate optimal analysis and initial conditions for forecast model
- Direct observations provide the necessary anchor for the non-direct observations in the system
- There is no need for tangent linear and adjoint of the forecast model.

The hybrid 4DEnVar GEOS data assimilation system (*cont.*)

- In addition to the static term, an ensemble of nonlinear model integrations over the data assimilation window provides the flow-dependent background error covariance, which renders cross-correlations among perturbations of control variables
- PBL-focused 4D data assimilation
  - Analysis of records/reanalysis for PBL thermodynamic structure & PBLH, towards coupled system
  - Model parameter estimation (Zhu and Navon 1999; Aksoy et al 2006)
  - Provide optimal initial conditions to NWP model – be aware that model forecast is also affected by
    - Balance among analysis variables -- how much/how long the analysis increments can be retained in the forecast
    - General forecast model bias – if not removed, analysis may or may not compensate forecast bias depending on whether good analysis or forecast is required
    - Process bias and compensating biases among different processes
    - Are the modern PBL schemes still highly dissipative? How sensitive are forecasts to changes in the PBL fields?

Point-wise correlation between cloud water and RH at 850hPa



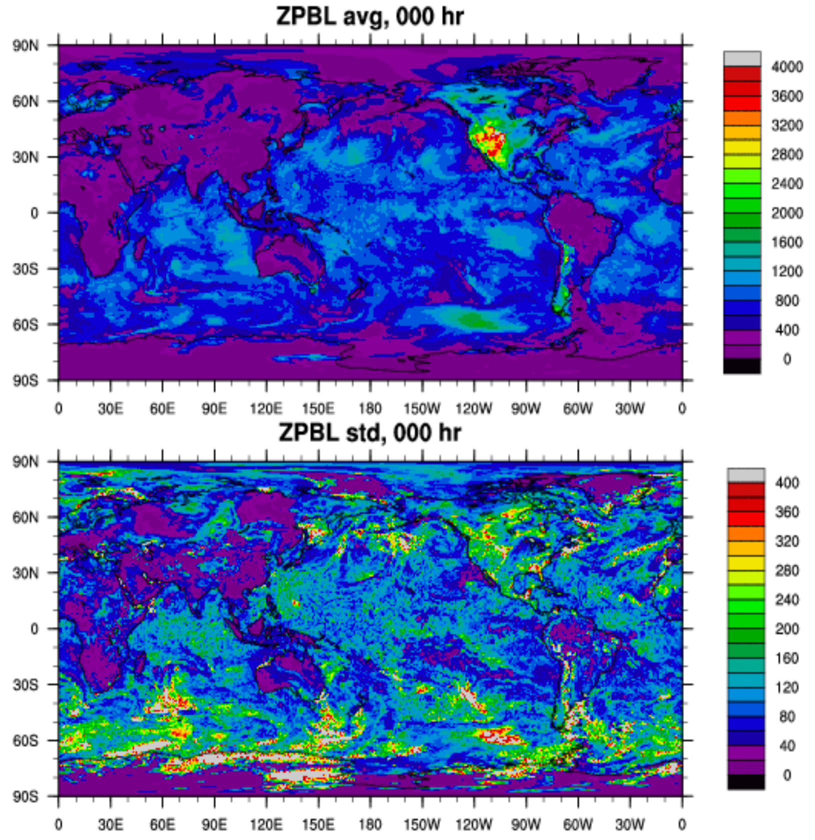
(Zhu et al 2019)

Initial condition sensitivity (W. McCarty)

Mean and standard deviation of PBL Height from a single set of ensemble forecasts
– Initialized at 0000 UTC on 11 Sept 2018
– 32 Members

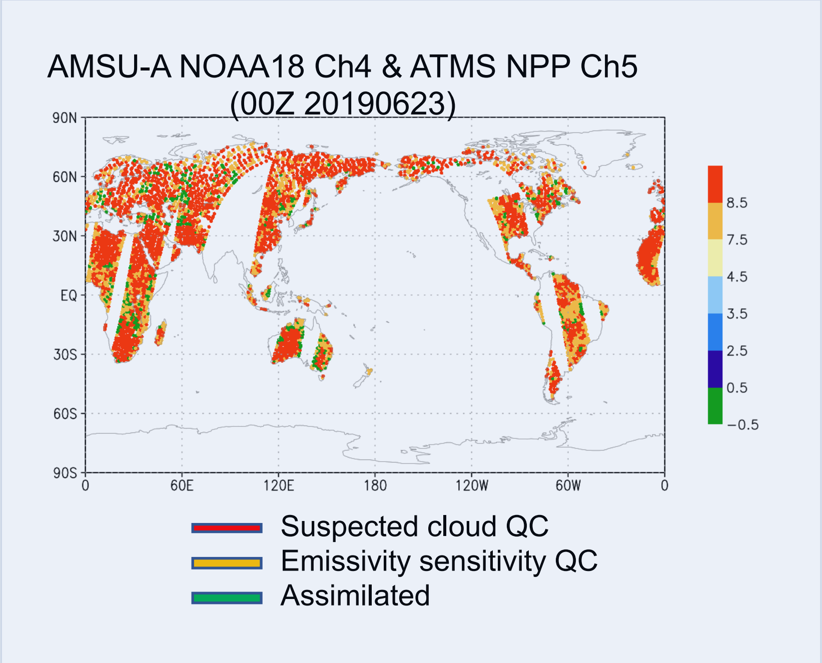
Over land, spread is correlated with PBLH and thus solar insolation. Over ocean, spread is largest over Southern Ocean.

Work is underway to run a larger suite of ensembles to help characterize PBL forecast sensitivity to initial conditions
– ~1 mon x 4 cycles per day x 32 members from EnKF

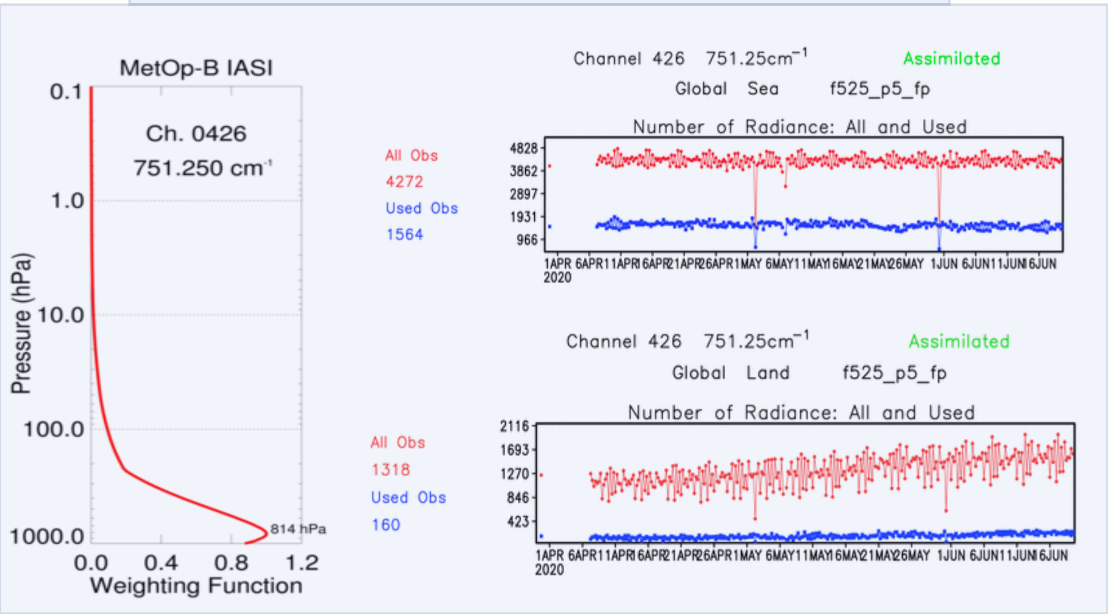


Assimilating surface-sensitive radiances over land is still challenging

- Large uncertainties of the land physical surface emissivity model used in the CRTM
- Uncertainties of land surface state properties



- Currently very few radiances are assimilated over land, large amount of radiances are rejected by
  - Emissivity sensitivity check
  - Cloud detection check
- WV & IR have different cloud detection algorithms
- Alternative cloud detection using cloud products, e.g., collocated VIIRS cloud product
- All-sky MW & IR radiance assimilation over land

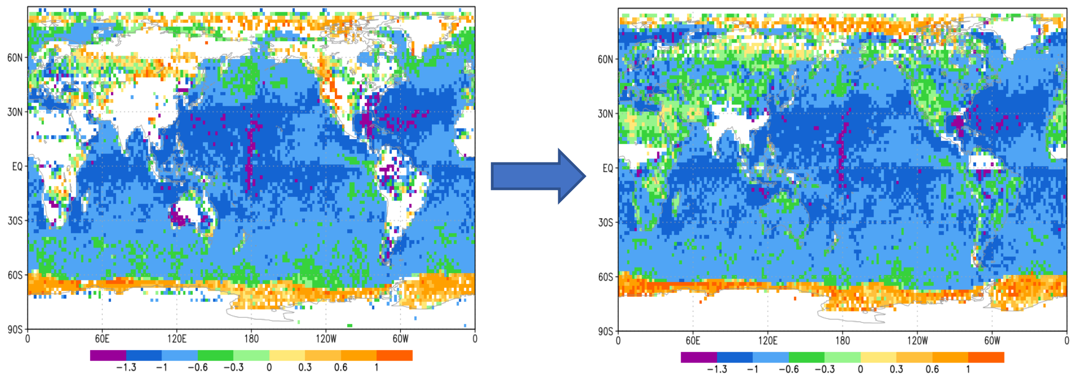


Instantaneous emissivity retrieval from the GEOS DAS system

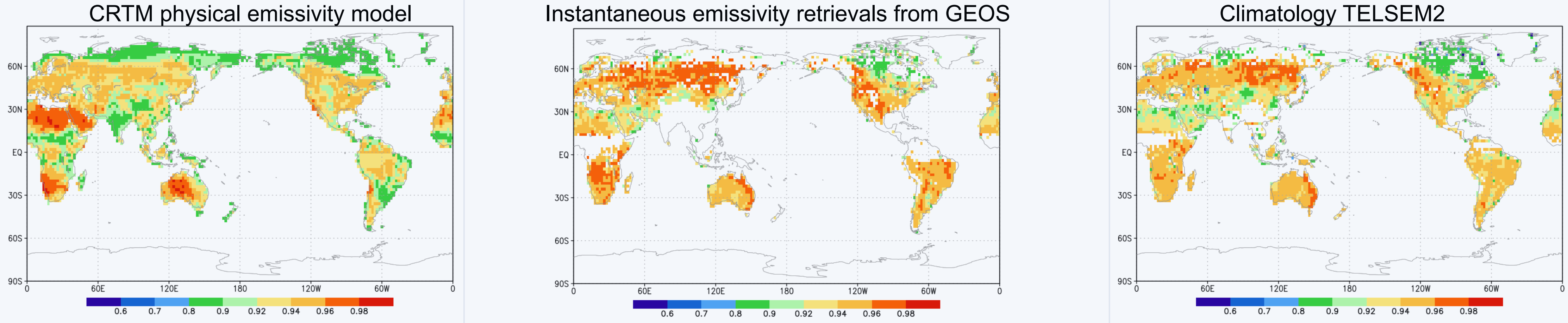
- For a scattering-free atmosphere, assuming a flat and specular surface, instantaneous surface emissivities are retrieved from MW window channels based on

$$R_{obs} = \varepsilon\, B(T_s)\Gamma + I_{up} + \Gamma\,(1 - \varepsilon)\, I_{down}$$

- The retrievals are used in the study of the assimilation of surface-sensitive sounding channels
- Cycled data assimilation experiments are underway

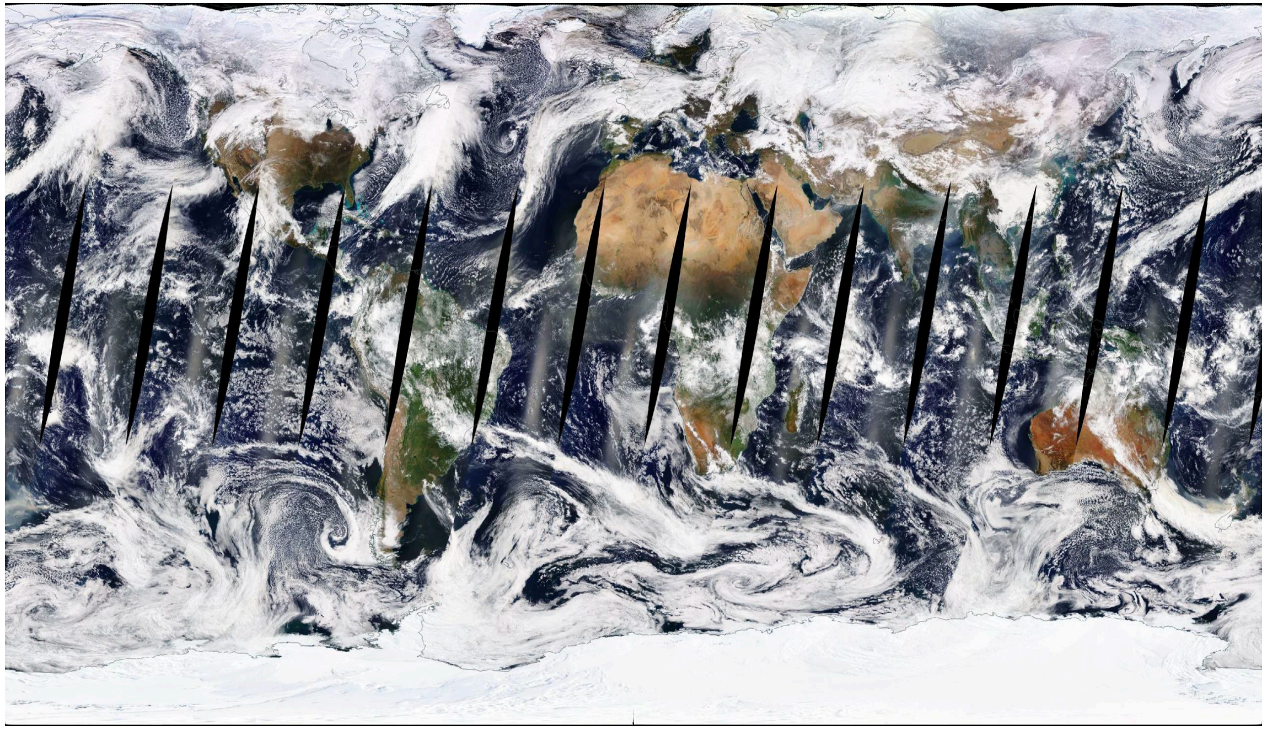


Monthly-mean OmF of assimilated 52.8GHz

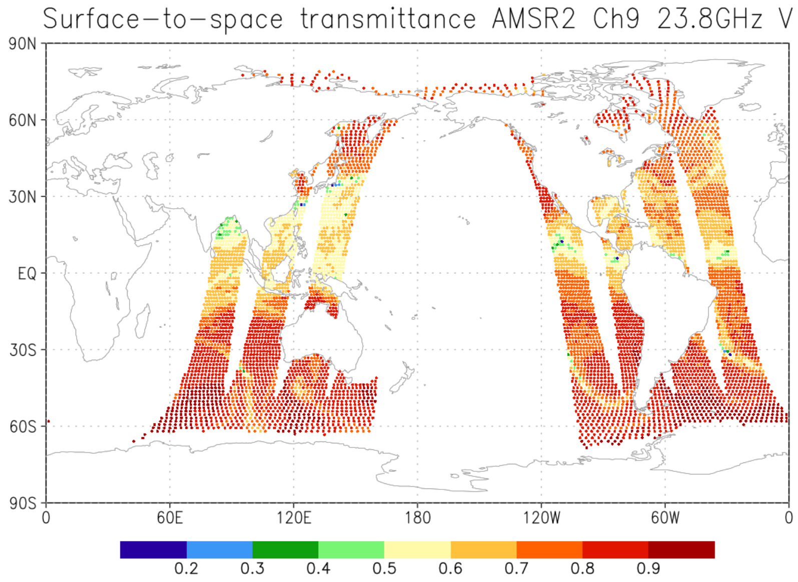


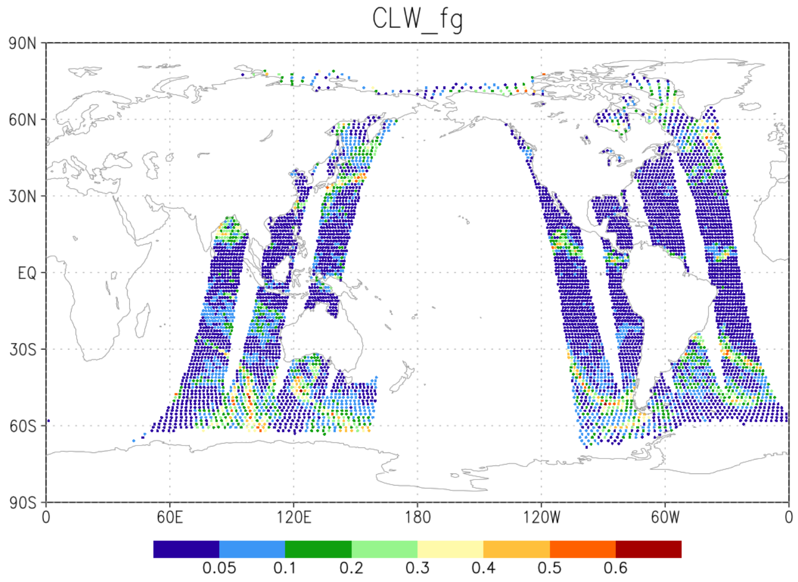
Monthly-mean emissivity for July 2019 AMSU-A N18 31.4GHz

The capability of microwave to “see” through clouds and precipitation



MODIS visible image on 2 February 2020 (c/o K. Lonitz)

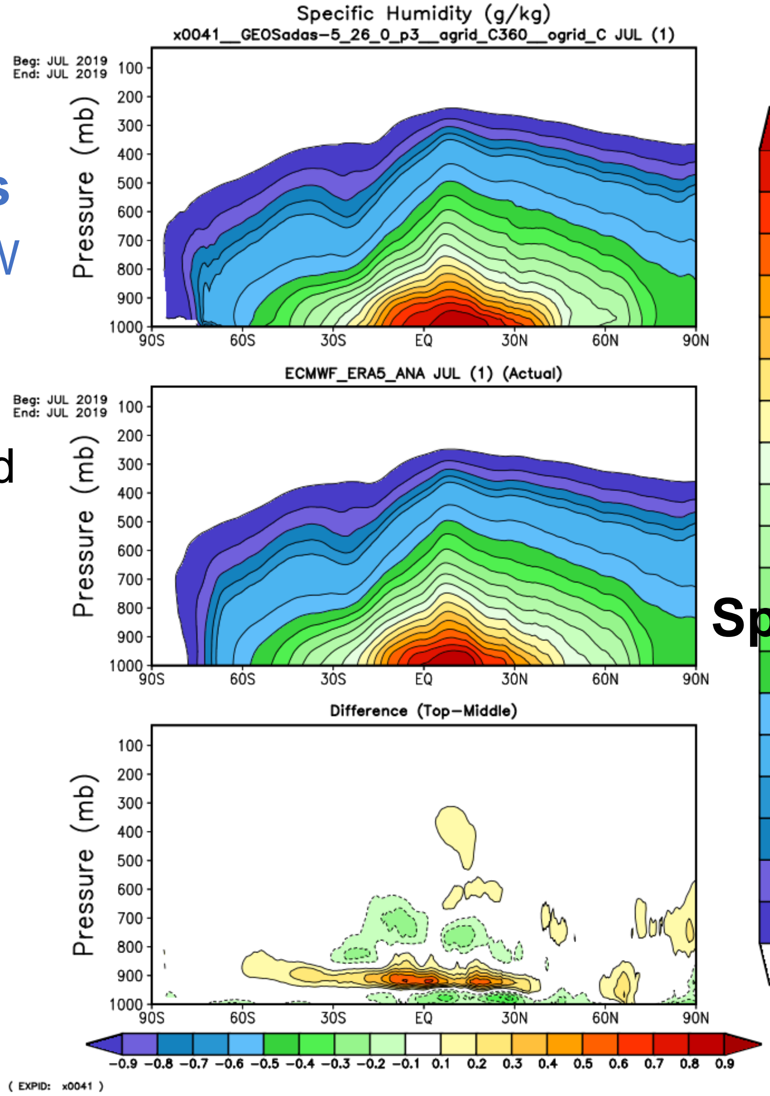




Impact of all-sky MW surface-sensitive radiances over ocean

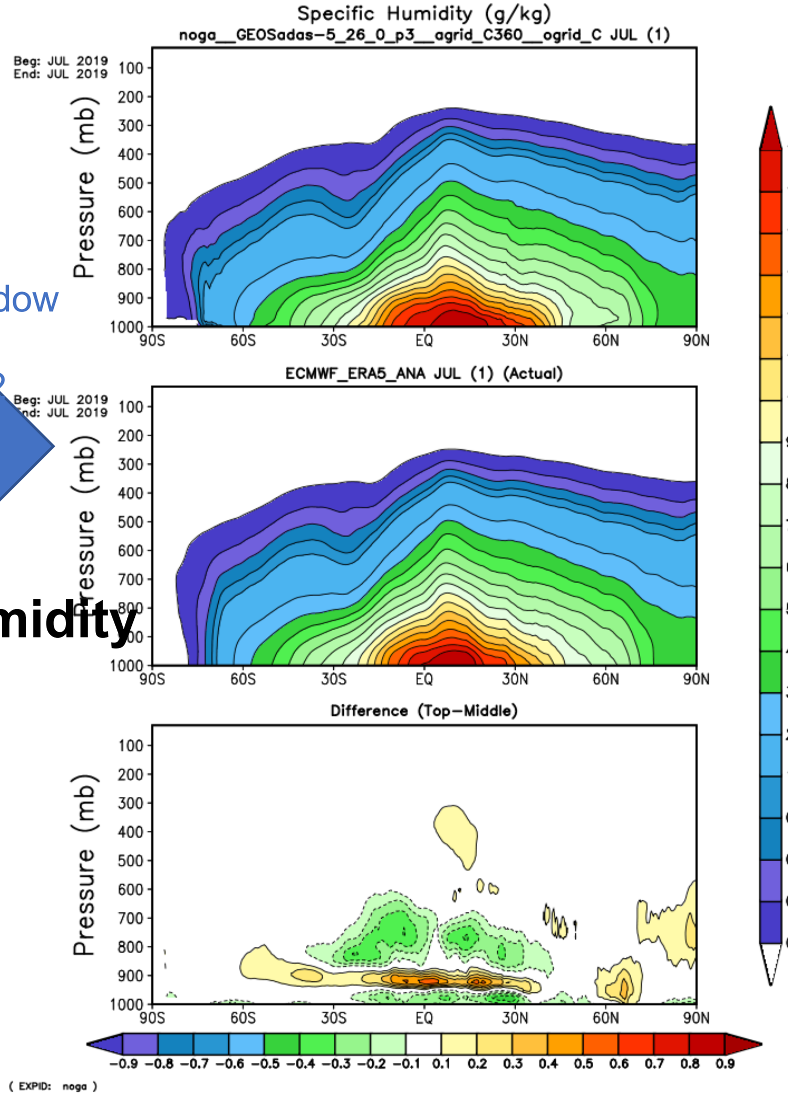
Data denial experiments showed that assimilating MW window channels from GMI+AMSR2 over ocean

- Improves q at 850hpa and 700hpa
- Degrades q at 925hpa in the tropics over ocean. Dry-mass constraint may have interfered with the all-sky MW radiances.



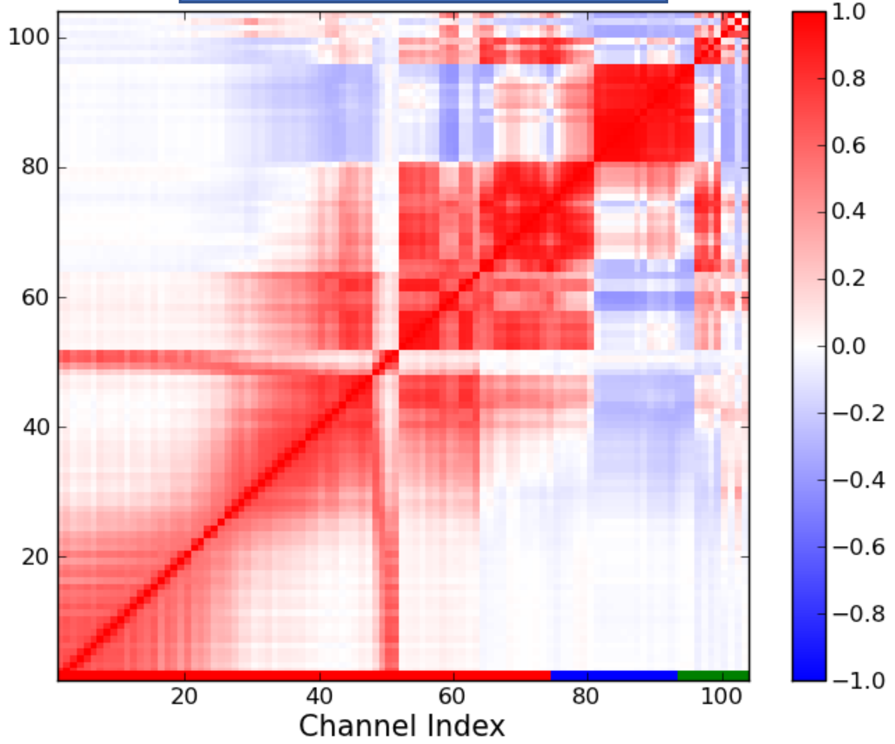
Remove window channels of GMI+AMSR2

Specific humidity vs ERA5



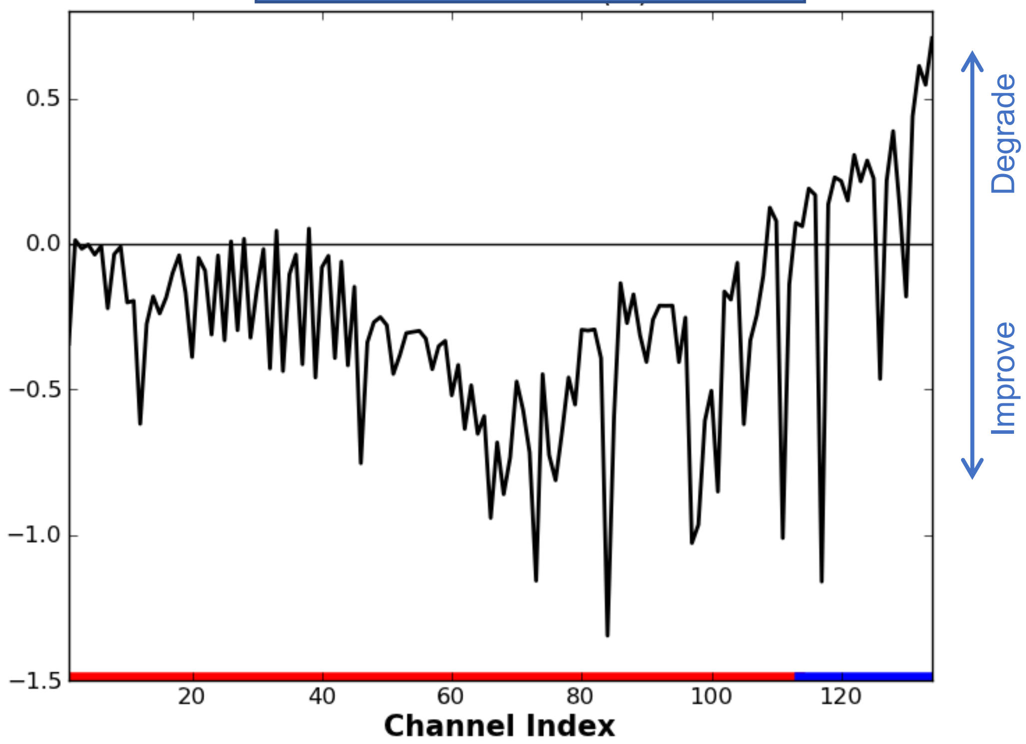
Correlated observation error for hyperspectral infrared CrIS-fsr radiances (Gu et al)

CrIS-fsr correlations



Large inter-channel correlations are seen for CrIS-fsr surface-sensitive channels

RMSE diff of IASI OmF

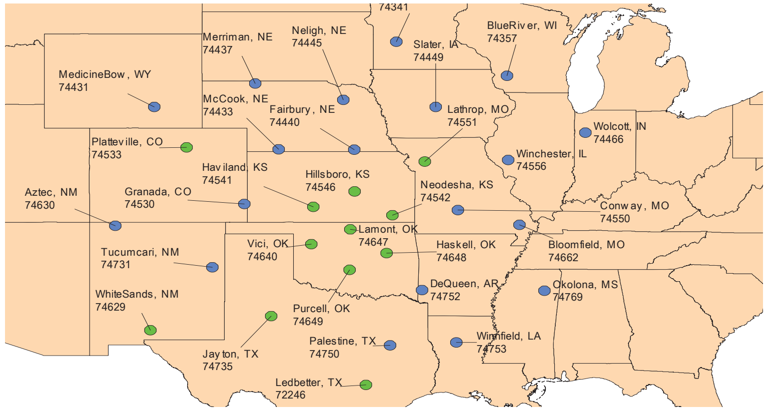


Response on IASI by two different treatments of CrIS observations

Planetary Boundary Layer Heights from Wind Profiler Backscatter Data

(Andrea Molod – GMAO, Haydee Salmun, Holly Josephs – Hunter College)

NOAA Wind Profiler Network



Global Wind Profiler Networks

Physical basis**:** The magnitude of the backscatter is related to the change in the index of refraction of the atmosphere (Bragg scatter). The gradients near the top of the boundary layer are manifest as maxima in backscatter.

Data that are Available Now

1) Hourly WP PBL heights at all stations from 1992-2012 (no data when PBL height is out of range, including nighttime and winter. Range gates every 250 m starting 500m above surface. Verification shows PBL heights to be reliable under clear sky conditions

2) Hourly Richardson-number derived PBL heights from 2000-2006 at the 7 RASS stations

"Pilot" Data Assimilation

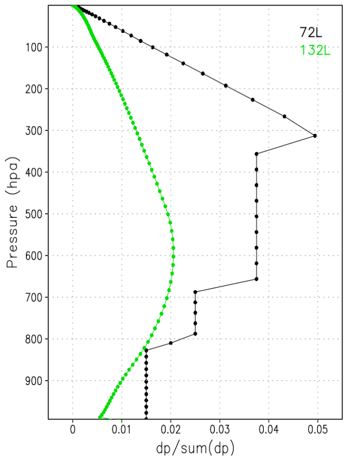
5 days in Sept, Oct of 2011 with "clear sky" PBL height data available at 20+ stations. Use model-calculated "Aerosol Mixed Layer Height" for backgrounds/correlations

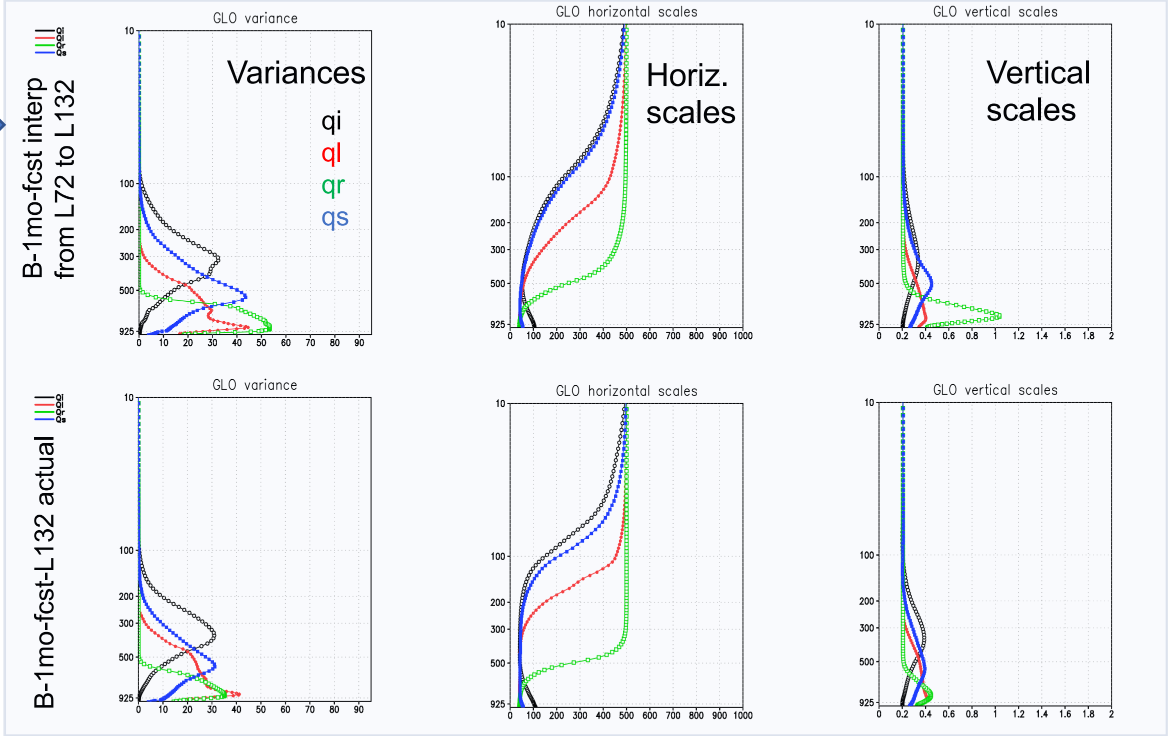
Towards high vertical resolution GEOS (R. Todling)

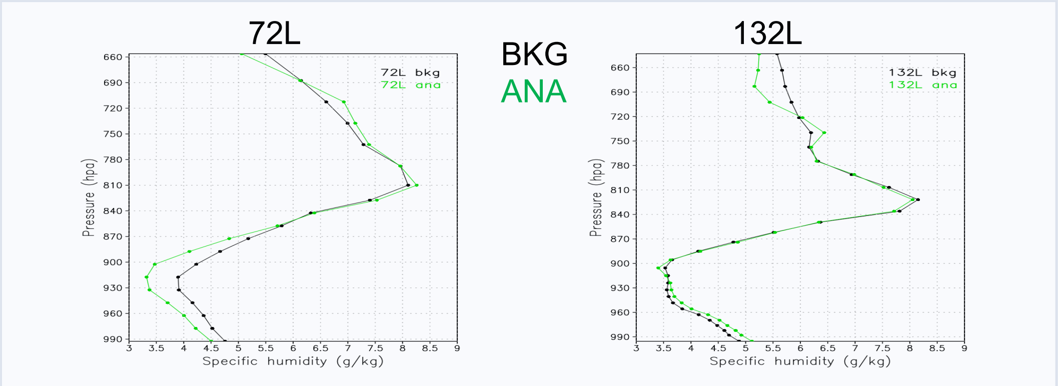
- Experimental DAS test:
    - Increase vertical levels from 72L to 132L
    - Derive and evaluate background error for 132L: Bclim + Bens
        - There is a lot of similarity of between the interpolated (L72->L132) background errors and the actual background errors (L132) derived from a one-month forecasts.
        - Some differences in the horiz scales of stream function; more substantial differences are seen in ql & qr, especially at lower levels or tropics
    - More detailed structure in the high-resolution run.
- Study with vertical resolution of 181L has been underway

72L vs 132L vert. levels

Below 800hpa:
13 levels
21 levels







23UTC Nov. 30, 2019 at (77W, 35N)

OSSEs for PBL study

- Retrieval and data assimilation could use OSSE framework to assist in mission design
  - Estimate effects of proposed instruments (and their competing designs) on analysis skill by exploiting simulated environment.
- Evaluate present and proposed techniques for data assimilation by exploiting known truth.
- Our Nature Run and existing baseline OSSE have been thoroughly validated for upper air. Efforts will be invested in the validation for the PBL.
- For performing OSSEs with surface-sensitive radiances, a perturbation model for the emissivity is needed, as this is a great source of error. The same is true for all-sky scattering coefficients.